Photon absorption on a neutron-proton pair in ^{3}He*

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Abstract

The cross section of the reaction $^3\mathrm{He}(\gamma,pn)p_{\mathrm{spec}}$ in the energy range 150 – 450 MeV has been calculated in a quasifree two-body model and compared with a recent kinematically complete experiment. In comparison with free deuteron disintegration the cross section is increased by a factor of about 1.5 in reasonable agreement with the data for photon energies above 200 MeV. At lower energies the data deviate from the two-body behaviour and thus suggest a more important role of the spectator requiring a more exact treatment.

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Some recent kinematically complete photoabsorption experiments on few-nucleon systems, notably on ^{3}He and ^{4}He, probe reaction mechanisms involving two or three nucleons. The choice of special kinematics with all momenta determined allows the explicit separation into two- or three-nucleon processes and thus facilitates detailed comparisons with specific theoretical models. Since each type of reactions can be considered separately, the usual ambiguities are diminished. In studies of "medium effects" in certain reaction mechanisms (albeit only few nucleons), one may consider reactions on two nucleons in the nuclear medium as the first frontier of interest by comparing with the free reactions on two nucleons. Unfortunately, there is only one bound two-nucleon system to compare with, namely the triplet-isosinglet deuteron, while in a nuclear environment also pairs with other quantum numbers, notably the $^1S_0$ isotriplet, become accessible.

The TAGX collaboration has extracted the photoabsorption cross section of a neutron-proton pair in ^{3}He in a kinematically complete experiment employing tagged photons in the intermediate energy range 150 - 450 MeV [1]. Also the angular distributions of both neutrons and protons in the quasi-two-body reaction are determined for 245 MeV photons. This explicit extraction goes beyond other, in many respects similar, experiments [2, 3], which typically give their results in the form of excitation functions at fixed single-nucleon angles. In the momentum dependence of these results it is possible to recognize a two-nucleon peak which can be compared with theoretical predictions [4]. However, the inherent presence of both the significant coherent multiparticle and the single nucleon background makes comparisons with models including just one mechanism less direct than in the case of Ref. [1].

There are two principal goals in two-nucleon absorption studies on nuclei. On the one hand, the presence of other nucleons may open new reaction mechanisms absent in the pure two-nucleon case. On the other hand, it leads to a modification of the participant two-nucleon wave function. A quasifree reaction mechanism rests on the assumption that the explicit effects from the remaining nucleons, i.e., spectators, can be neglected and that they retain their initial Fermi motion distribution in the final state. In that case information about the wave functions and correlations in the medium can be obtained, provided the corresponding quasifree reaction, here the two-body reaction, itself is understood.

Apart from the presence of the spectator, the main difference of a quasideuteron in ^{3}He as compared with the free deuteron is that its wave function is more compressed to short distances with an enhanced D-state probability. In the case of pion absorption, these differences cause large effects in both the magnitude of the cross section and in spin observables [5]. Similar changes could be expected also in the quasideuteron dominated part of photodisintegration. In this letter we give a comparison of a theoretical calculation of photoabsorption on a bound nucleon pair with the experiment of Ref. [1]. We see that the change of the wave function alone is sufficient to explain largely the differences between the data of Ref. [1] and the free deuteron photodisintegration data.

The basic ingredients of the model are identical to free deuteron photodisintegration [6, 7] and will not be repeated here, except that the model includes the usual one-nucleon current alongwith the Siegert operators and explicit pion and ρ-meson exchange currents beyond the Siegert operators. The particularly important contribution at intermediate energies, the M1 excitation of the $\Delta(1232)$-isobar, is incorporated in a coupled channel approach as developed for deuteron photodisintegration in Refs. [6, 7]. Allowing for a phenomenological adjustment of the $\gamma N\Delta$-coupling in Ref. [7], this model gives a satisfactory description of the energy dependence of the free cross section at intermediate energies. Photodisintegration of the $^1S_0(np)$ pair in ^{3}He is coherent and experimentally inseparable from the photon absorption on a quasideuteron. Partly due to the lack of a strong Δ contribution in the magnetic dipole transition in this case [8], it is, however, a very minor effect in the energy range of the experiments of Refs. [1, 2, 3], but for completeness it is included in our calculation.

The spin-isospin weights in ^{3}He give for the overall probability of a particular two-nucleon pair to form a quasideuteron ($T = 0, S = 1$) the value 1/2 and 1/6 for a $^1S_0(np)$ pair. The remaining probability 1/3 is for the $^1S_0(pp)$ pair. This yields for the cross section of absorption on an np pair (the observable extracted in Ref. [1])

$$\sigma_{\mathrm{He}}(np) = \frac{1}{2}\,\sigma_{qd} + \frac{1}{6}\,\sigma_s \qquad (1)$$

with a corresponding relation for the differential cross sections. Here $\sigma_{\mathrm{He}}(np)$, σ_{qd} and σ_s are the *two-body* cross sections for absorption on ^{3}He, the quasideuteron and the $^1S_0(np)$

pair, respectively. More details on the cross sections and also spin observables will be given in Ref. [8].

The S-wave part of the quasideuteron wave function is taken from the correlation function of Friar et al. [9], obtained in a Faddeev calculation using the Reid soft core potential. This can be fitted in a smooth way by multiplying the normal deuteron wave function by a simple radial function [5]. This wave function is supplemented by a D-state obtained by multiplying the deuteron D-wave part by the same radial function giving for the D-state probability $P_D(^3\text{He}) = 10.5\%$ in line with several Faddeev calculations.

Our main result for the energy dependence of the total cross section is given in Fig. 1. The solid curves show the full results for two-body absorption on ^{3}He (the upper curve) and on the deuteron. There is an increase by roughly a factor of 1.5 to be compared with the experimental observation 1.24 ± 0.26 [1]. However, contrary to the suggestion given in Ref. [1], the calculated enhancement is not due to the frequently presented argument that there are 1.5 quasideuteron pairs in ^{3}He. This number of pairs is obtained as one half (the above mentioned probability) of the number of different ways of forming a pair among three particles. However, for identical particles (in the isospin formalism the proton and neutron can be considered as indistinguishable) the total cross section must be divided by 3! [10]. Considering a factor 1/2 out of 1/3! to be included in the two-body cross section itself, this leaves 1/3, cancelling the "number of pairs" or rather the number of indistinguishable permutations with respect to the spectator. In fact, in Fig. 1 the quasideuteron result has been already reduced by the factor 1/2 of Eq. (1). The pure wave function effect would have been an enhancement by a factor of about 3 over the free reaction. Therefore, an interpretation of the experimental result as just a statistical factor effect in comparison with the true two-body reaction, i.e., ignoring the wave function effect completely, would be erroneous. The dashed curve shows the pure quasideuteron contribution leaving out the $^1S_0(np)$ part. The change is, however, quite small except at lower energies, partly reflecting the importance of the Δ contribution in the quasideuteron process and partly being simply due to the additional relative weight 1/3 for the $^1S_0(np)$ component of the cross section in Eq. (1).

Except for the decrease of the cross section data below 200 MeV, which cannot be

reproduced, the theoretical result is quite reasonable. A mere scaling of the free reaction cross section also fails to produce this behaviour at lower energies. One possible explanation is a destructive interference with the spectator, arising at lower energies. The distribution of the Fermi momentum could allow for a significant contribution from this interference up to 200 MeV/c nucleon momenta. Furthermore, the calculation slightly overestimates the cross section. This overestimation above 250 MeV could be compensated for by a slight downshift in energy of the theory, which could be interpreted as a stronger Δ attraction in the three-nucleon system than in the two-body system. However, the calculation is still nearly within the experimental errors and, in fact, Ref. [2] gives a somewhat larger cross section for two-nucleon absorption with $\sigma_{\mathrm{He}}/\sigma_d = 1.68 \pm 0.07$ obtained from the proton excitation function in (γ, p) reactions.

In Fig. 2 we present a comparison of the angular distribution at 245 MeV between our model results and the data of Ref. [1] for neutrons (full curve, full circles) and protons (dotted curve, open circles). The comparison of the neutron results is more direct, since it avoids a possible participation of the spectator. Considering the significant error limits in the data, the model agrees with the experiment quite satisfactorily. The proton distribution is easier to measure and has smaller errors. However, the experimental indistinguishability of the spectator would, in principle, make its more explicit treatment necessary also in the model cross section. In the dotted curve we have simply added incoherently the two-body proton cross section $d\sigma/d\Omega_p$ and an isotropic spectator cross section $\sigma_{\mathrm{He}}(np)/4\pi$. The model does, indeed, give a more forward peaked proton distribution than the neutron one in agreement with the data. However, the proton cross section is too high, which is also reflected in the total cross section.

In summary, we have calculated quasideuteron photodisintegration with a modified deuteron wave function and compared to the quasifree photoabsorption on an *np* pair measured in Ref. [1]. The embedding of the quasideuteron in ^{3}He leads to a probability factor 1/2 in the cross section. In addition, we have included the experimentally indistinguishable absorption on the $^1S_0(np)$ pair in ^{3}He. Although there appears some slight deviation in the proton cross section, where also the spectator may contribute, the overall results are satisfactory and largely support the quasifree assumption for the proper

kinematic conditions. The low energy behaviour requires more detailed work. Purely compressing the two-body wave function to shorter distances in ^{3}He causes an increase in the cross section by a factor of about 3. This is reduced to about 1.5 by the above discussed probability factor 1/2 for finding a quasideuteron in ^{3}He. One can, indeed, expect an increase in the transition matrix elements for both one- and two-body contributions to the electromagnetic current. The latter are shorter-ranged and their contributions obviously benefit from the initial pairs concentrated at shorter distances. The nucleon scattering function in turn makes the one-body current amplitude essentially a Fourier transform of the bound pair wave function. At the rather high momentum transfers relevant here also this becomes larger. This interplay of different mechanisms versus properties of the bound pair wave function will be discussed in more detail in a forthcoming paper [8].

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Figure captions

Fig. 1. The total cross section of the quasifree reaction $^3\mathrm{He}(\gamma, pn)p_{\mathrm{spec}}$. The solid curves present the full result for ^{3}He (upper) and deuteron (lower). The dashed curve describes photon absorption on the pure quasideuteron in ^{3}He without the singlet contribution and the dotted absorption on the $^1S_0$ pair alone. The data are from Ref. [1].

Fig. 2. The differential cross section of two-nucleon photodisintegration in ^{3}He at 245 MeV photon energy. The solid curve and full circles correspond to the neutron, the dotted curve and open circles to the proton cross section. The data are from Ref. [1].

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